

THE AERONAUTICAL DATA LINK: DECISION FRAMEWORK FOR ARCHITECTURE ANALYSIS

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Abstract

A decision analytic approach that develops optimal data link architecture configuration and behavior to meet multiple conflicting objectives of concurrent and different airspace operations functions has previously been developed. The approach, premised on a formal taxonomic classification that correlates data link performance with operations requirements, information requirements, and implementing technologies, provides a coherent methodology for data link architectural analysis from top-down and bottom-up perspectives. This paper follows the previous research by providing more specific approaches for mapping and transitioning between the lower levels of the decision framework. The goal of the architectural analysis methodology is to assess the impact of specific architecture configurations and behaviors on the efficiency, capacity, and safety of operations. This necessarily involves understanding the various capabilities, system level performance issues and performance and interface concepts related to the conceptual purpose of the architecture and to the underlying data link technologies. Efficient and goal-directed data link architectural network configuration is conditioned on quantifying the risks and uncertainties associated with complex structural interface decisions. Deterministic and stochastic optimal design approaches will be discussed that maximize the effectiveness of architectural designs.

1 Introduction

The future Communication, Navigation, and Surveillance/Air Traffic Management (CNS/ATM) system will rely on global ground-based and satellite-based navigation and communications via the Aeronautical Telecommunications Network (ATN). The ATN is a large complex system whose behavior is a response to both discrete-time events

(those associated with digital flight control computers and clocked data links) and continuous-time events (those associated with flight operations). Data links are telecommunication networks that allow for digital transmission of data to all users in the National Airspace System. Data links will provide significant benefit to air traffic management by greatly improving air traffic control operations through more timely, reliable, and efficient information transfer. Designing and configuring aeronautical data link systems, however, is a complex undertaking involving the simultaneous satisfaction of conflicting criteria related to operations requirements, information system performance requirements, available telecommunications technology capability, and existing and proposed data link services.



Figure 1. Data Link Decision Framework

A decision analytic approach that develops optimal data link architecture configuration and behavior to meet multiple conflicting objectives has been previously developed [1]. This paper continues the previous research by providing more specific approaches for mapping and transitioning between the levels of the decision framework (Figure 1). The previous work applied the decision

methodology to a Small Aircraft Transportation System (SATS) High Volume Operational (HVO) Concept. Though the SATS example was limited in scope, the analysis provided sufficient insight into how to pose “what if” questions, where to incorporate external analysis tools, ways to manage decision uncertainty, and techniques used to select optimized data link architectures in the presence of conflicting constraints. Application of the decision framework to the SATS example was a Level 0 through Level 2 top-down process resulting in the selection of a data link service and a confirmation of its capability to provide the information performance to support the HVO required operations. This paper will continue the application of the decision methodology to the SATS HVO example. The current research will describe a different process to determine the required capabilities from the operational requirements (a Level 0 to Level 1 top-down transition) as well as augment the previous research by developing a process that obtains the required technology performance parameters that meets the required system performance (a Level 2 to Level 3 top-down transition).

1.1 Complex Data Link Decisions

Information networks in the current airspace system are, for the most part, isolated from each other. This fragmentation is beneficial because it allows simple, locally optimized architecture design and usage decisions, yet detrimental because it impedes decisions that yield system-wide optimization. The incorporation of new concepts such as the ATN that provide a unified framework will enable globally optimal decision making by aeronautical telecommunications practitioners. Unified frameworks also have the disadvantage of increased complexity that results from the interaction of highly coupled dissimilar systems. To exploit the efficiencies of unified concepts while mitigating the effects of complexity will require a change from the current reductionist view of decision-making to one that is more systems oriented [2]. The purpose of the data link decision framework is to authorize a methodology that manages the interdependencies and the resulting complexity of the decision in a way that allows for intelligent and meaningful analysis in a systems-oriented fashion.

1.2 Assumptions and Organization

Two assumptions guide the development of the decision framework. The first is that a database exists and is populated with complete informational content sufficient to support a formal taxonomic classification of data link systems. Currently, there is no single unified database, though the data that would comprise it exists in distributed locations. Methods and techniques that create a virtual database from distributed sources exist [3]. The second is an implicit assumption that there is no completely objective theory of decision-making [4]. Each tool or technique possesses trade-offs and the selection of said methods must be based on the objectives of the end user.

This paper is organized as follows. Section 1 provides background information on data link related decisions as well as the purpose of the current research. Section 2 will describe various issues related to complex decision making. Section 3 will provide a general overview of the various components of the decision framework. Section 4 will apply the decision analysis process to the SATS HVO Concept using several methods. The first method uses a linear programming technique to derive operational requirements from the operations concept. The second method provides a probabilistic quantification of required capabilities from the operational requirements (a Level 0 to Level 1 top-down transition process). The third method uses Shannon’s Information Capacity Theorem to obtain the required technology performance parameters that meet the SATS HVO required system performance (a Level 2 to Level 3 top-down transition process).

2 Fundamental Issues of Complex Decisions

Data link decisions involve the following issues: decision coherency, qualitative/quantitative analysis, and entropy management.

2.1 Decision Coherency and Cohesiveness

Decision coherency, in the sense of complex data link architecture selection, means that one’s operational scenarios and requirements, one’s selected capabilities, and one’s system performance parameters must be internally consistent with the selected technology performance. This necessarily

states that the tools and techniques used to determine performance and integrity assessments must follow mathematical, probabilistic, and set theory laws. It does not, however, have to exist in reality (i.e., designing new data link technologies).

2.2 Qualitative Aspects of Complex Decisions

The goal of qualitative analysis is to establish a structure for the problem in which the behavior of the system can be inferred. Qualitative reasoning with respect to physical systems relies on the relationships between: structure (or configuration); behavior – a sequence of states that a system and its components exhibit over some time-interval; and function – the purpose of structure in producing the behavior of a system. The behavior of a system results from interactions between the behaviors of its components. The effects of a change in the state of one component propagate locally through structural connections causing a change in the state of other components and of the system as a whole. The end user must ensure that the qualitative aspects of the decision model are appropriate and reasonable to the problem at hand.

2.3 Quantitative Aspects of Complex Decisions

Quantitative models have wide applicability in engineering, operations research and financial decision-making. The goal of quantitative modeling is to manipulate certain decision variables in order to optimize one or a set of objective functions that are of interest to the end user. With numerous quantitative approaches available, the end user has various mathematical or graphical representations from which to choose. Some of these quantitative techniques include linear programming models, simulation models, network models, probability models, multi-objective decision models, queuing formalisms, and more. As in the qualitative case, the end user must ensure that the quantitative model is applicable to the problem at hand.

2.4 Decision Entropy

Entropy, in the context of decision analysis, is a measure of the amount of uncertainty represented in a decision and is a measure of the available information about a system. If the system state is completely known, then entropy is precisely zero. Unfortunately, complete knowledge of system state for complex data link problems is rarely known.

Entropy, in a realistic case, must be identified and managed. Sources that contribute to overall entropy include the appropriateness of the qualitative structure of the model, the precision of the quantitative approach, the completeness of the data, the coherency of user preferences, the specificity of the operational requirements, uncertainties involving numerical scaling, the selection of appropriate aggregation techniques, as well as the effectiveness of encoding the environmental context of the problem. Entropy provides some measure of reliability or confidence to the analytical results.

3 Data Link Decision Framework

The data link decision framework is a decision analysis tool that aids users in obtaining optimized data link architecture configurations and behaviors. The partitioned structure of the framework (Figure 1) allows users with vastly different goals to become engaged in the methodology.

3.1 The Data Link Methodology

The data link decision framework (Figure 1) is a decision-analytic process that simplifies data link complexity by partitioning the analysis among four different levels (Levels 0-3). Subsequently, each of the four levels partitions the multi-objective analysis from high-level constituents (mostly qualitative decision variables) to low-level constituents (quantitative decision variables). Level 0 involves information related to high-level operational concepts. Level 1 contains information capabilities that guide data link services. Level 2 includes information related to system level data link performance. Level 3 comprises information related to various data link technologies. The traversal between levels involves the acquisition of more detailed parametric information. The highest level (Level 0) can be thought of as a conceptual level whereas the lowest level (Level 3) consists of parameters that can be implemented in hardware. Conceptually, the process of data link solution selection is posed as a multi-objective decision analysis problem.

3.2 Data Link Taxonomy

The data link taxonomy (Figure 2) is organized hierarchically, that is, from conceptual to implementation information types (Levels 0 to 3,

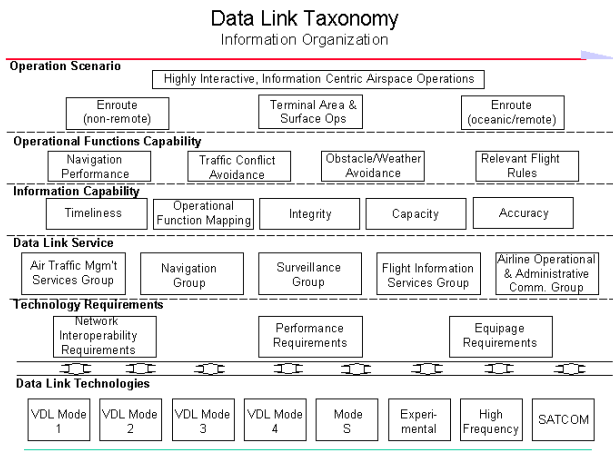


Figure 2. Data Link Taxonomy

respectively). The taxonomy is also relational in that all the information on one level is mapped vertically to each adjacent level as well as horizontally to elements and parameters on the same level. Taxonomy content is linked with levels in the decision methodology.

3.3 The Multi-Dimensional Database

The information required for objective and meaningful analysis is clustered in a multi-dimensional database organized according to a data link taxonomy (see Section 1.2 for stated assumptions). This multi-dimensional structure best accommodates the information content and relational aspects of the data link taxonomy. For proper analysis, the database is intended to be accurate and complete. The database is populated from data link equipment manufacturers and experimental testing reports as well as information contained in data link standards documents (e.g., RTCA MOPS, MASPS, etc.).

3.4 Architectural Analysis

Architectural analysis is the process of utilizing analytical tools to answer qualitative or quantitative questions regarding data link architectures (whether informational, system-level, or technology-based). Given the large number of possible decision variables, there are a large number of possible architectures from which to choose. Simply stated, the process of finding a candidate set of functionally compatible architectures involves identifying the data link services (applications) required, determining the constraints used to

confine the feasible region of solutions, and applying an analytical tool to select the most desirable candidate from the set. The decision framework permits data link architectural analyses from both top-down and bottom-up perspectives. The top-down perspective allows a user to formulate a data link design concept and then successively refine the capability, system and technology requirements. The bottom-up perspective allows the user to acquire data link technologies already available and gradually build larger system level architectures.

4 Transitioning in the Decision Framework

The following example will apply the data link decision framework to the Higher Volume Operation (HVO) at Non-Towered/Non-Radar Airports, one of the four operating capabilities of the Small Aircraft Transportation System (SATS) concept currently under development by NASA, the FAA, and local aviation and airport authorities. A draft Concept of Operations (CONOPS) document [5] defines the 2010 SATS operating capabilities. Three analytical tools will be applied to execute the transition from Level 0 to Level 3. First, a Linear Programming technique will establish the operational requirements (Level 0) based on the operations concept. Second, a probabilistic quantification approach will determine the required capabilities from the operational requirements (a Level 0 to Level 1 top-down transition process). Third, Shannon's Information Capacity Theorem will provide the basis for computing the required technology performance parameters that meet the SATS HVO required system performance (a Level 2 to Level 3 top-down transition process).

As described above, the framework is a decision support tool that guides the decision process in both top-down and bottom-up directions. The top-down direction translates operational requirements into increasingly detailed information requirements from desired data link capability through data link system performance requirements to implementation technology performance requirements. The bottom-up assessment delineates and selects data link capability options from available technologies. The framework consists of four levels designated zero through three. Each

Supported Operations HVO Operational Requirements - Level 0							
Operational Function	Required Operation						
	File HVO/FR Flight Plan	Departure/ Arrival Request	Departure/ Arrival Assignment	Takeoff/ Approach	Transition To/From ATC		
Traffic Density		# Aircraft	# Aircraft				
Op. Time Window							
Requested Nav. Parameters		Req'd Signal					
• Dep./Arr. Fix		Dest. Pos.					
• Dep./Arr. Time		Time					
• A/C State		Pos./Vel.					
Assigned Nav. Parameters			Queue Pos.				
• Sequence			Time				
• Dep./Arr. Time			1 st Leg Vel.				
• Velocity							
Self-Sequencing				Traj. Intent	Traj. Intent		
Self-Separation				Req'd Nav. Perf. Acc'y. (nm, kts)			
Release To/From ATC					Sig. Acq. Range		

Figure 3. Level 0 Matrix

level is a matrix whose elements are the quantitative performance requirements for the next level. The tool is designed such that a decision process can be initiated at any level or conducted in any direction, depending on the required decision and the available data.

The information in the Level 0 matrix for HVO (Figure 3) is derived from the draft SATS CONOPS 2010 document [5]. The matrix encapsulates the required operations (horizontal label), the functions necessary to complete the operations (vertical label), and the performance parameters required to execute the functions (matrix elements). In order to transition to Level 1, estimated values for the performance parameters are required.

As an example of the application of the framework, a four aircraft approach scenario is developed. Any number of aircraft can be included in the scenario. Four have been chosen primarily to keep the Level Matrix figures at a manageable size for illustrative purposes. Four is also a reasonable number for a general aviation, non-towered airport to expect to accommodate in a small time period. The scenario's operational parameters are: each aircraft executes a two leg path to a common final approach point, each aircraft self-separates and self-sequences at the approach point, the leg distances and headings of each aircraft are varied with no particular pattern, all aircraft are at roughly the same altitude, and the time window for all aircraft to transition through the approach point is 15 minutes. The maximum distance traveled by an aircraft from initiation to approach point is 41 nautical miles. Figure 4 is a notional illustration of the scenario. For this example, a linear

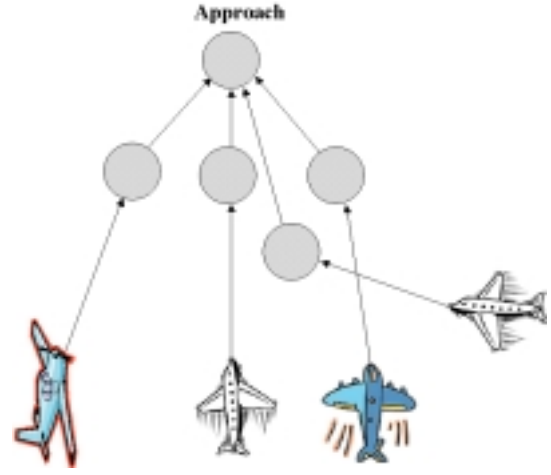


Figure 4. Four Aircraft Approach Scenario

programming method called goal programming is used [6]. The primary reasons for selecting this method are the ability to model trajectories with multiple heading changes for any number of aircraft, the implicit computation of trajectory deviation while optimizing the performance parameter of interest, and the wide availability of computational tools for the method. Most commercial spreadsheet applications include optimization capability and there are several books [7, 8] that develop goal-programming models within the applications.

The goal-programming model for HVO is:

$$\min Z = \sum_i \sum_j (d_{ij}^- + d_{ij}^+) \quad (1)$$

subject to :

$$X_{ij-1} + \sum_k \left\{ \frac{1}{k} \sec \theta_{ij} (t_{ij} \pm (i-1)(\delta t_{ij})) V_{ijk-1} + \frac{1}{k} \sec \theta_{ij} (t_{ij} \pm (i-1)(\delta t_{ij})) V_{ijk} \right\} + d_{ij}^- - d_{ij}^+ = X_{ij}, \quad (2)$$

$$V_{ij} \leq V_{MAX},$$

$$V_{ij} \geq V_{MIN},$$

$$i = 1, M; \quad j = 1, N \quad \text{and} \quad k = 1, P$$

where

M = number of aircraft,

N = number of legs,

P = number of leg segments,

X_{ij-1} = initial position of Aircraft i for leg j ,

X_{ij} = destination of Aircraft i for leg j ,

Estimation of Level 0 Performance Parameters
Information Performance Requirements - Level 0

Performance Parameter	Operation Time Window	Operational Function																Release Fulfillment ATC
		Requested Navigation Parameters				Assigned Navigation Parameters				Self Sequencing				Self Separation				
Aircraft #		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
Initial Velocity (kts)	15 min	130	130	120	130													
Leg 1 Dist. (nm)	15 min	25	24	25	26													
Leg 1 Time (min)	15 min	12.60	11.80	12.5	13	12.60	11.80	12.5	13									30 min
Leg 1 End Vel (kts)	15 min					120	120	120	120									
Leg 1 Vel Adj (kts)	15 min									0	0	0	0					
Leg 1 End Vel (kts)	15 min									120	120	120	120					
Leg 1 EPU (nm)	15 min													0.0	0.0	0.0	0.0	
Leg 1 EVU (nm/s)	15 min													0.0	0.0	0.0	0.0	
Leg 2 Dist. (nm)	15 min	12.5	18	12.5	15.2													
Leg 2 Rel. Hdg. (°)	15 min	22.3	30.0	-22.3	31.3													
Leg 2 Time (min)	15 min	6.25	5	6.25	7.6	6.25	6.2	6.34	7.1									
Leg 2 Velocity (kts)	15 min					80	80	80	80									
Approach Vel. (kts)	15 min					80	80	80	80									
App Vel Adj (kts)	15 min									12	3.08	0	-8.1					
Approach Vel. (kts)	15 min									80	80	80	78.9					
Leg 2 EPU (nm)	15 min													3.5	1.7	0	2.3	
Leg 2 EVU (nm/s)	15 min													36	84	0	86	

Figure 5. HVO 4 Aircraft Approach Operation

d_{ij}^- = underachievement of X_{ij} ,

d_{ij}^+ = overachievement of X_{ij} ,

θ_{ij} = heading of leg j relative to leg j-1,

t_{ij} = elapsed time of Aircraft i on leg j,

V_{ijk} = velocity of Aircraft i at end of leg j,

V_{ijk-1} = velocity of Aircraft i at start of leg j,

V_{MAX} = maximum speed for Aircraft i,

V_{MIN} = minimum speed for Aircraft i,

δt_{ij} = sequencing time delay for Aircraft i
on leg j = N-1, and 0 elsewhere.

The sequencing time delay chosen for the scenario ensures that there is a one-minute separation in arrival at the approach point between each aircraft. The model solution selects common aircraft velocities for each leg and the position error at the end each leg for each aircraft such that the 15-minute window requirement is approximately met. Individual velocity adjustments to eliminate position error for each aircraft can be computed using equations (4) and (5),

$$\text{leg velocity adjustment} = V_{ijk}^* - V_{ijk} \quad (4)$$

where

$$V_{ijk}^* = \frac{X_{ij}(V_{ijk} - V_{ijk-1})}{X_{ij} - d_{ij}} + V_{ijk-1} \quad (5)$$

Figure 5 displays the computed Level 0 performance requirements to execute the four aircraft operational scenario.

4.1 Transitioning Between Level 0 and Level 1

Level 0 to Level 1 mapping establishes in a very basic form the informational infrastructure needed to support the required operations and operational functions. The result of this transition is the identification of data link capabilities required to satisfy infrastructure needs. This Level 0 to Level 1 top-down transition process will employ a probabilistic Bayesian network approach. The quantified informational infrastructure requirements that support the required data link capabilities will be displayed in the Level 1 matrix.

4.1.1 Outputs and Constraints of This Transition

The transformation between Level 0 and Level 1 involves identifying and extracting the informational components required to perform the operational functions and the derivation of requirements necessary to enable the operational functions. This informational infrastructure constrains the set of available data link services to those that satisfy infrastructure needs. In order to transition to Level 1, operational requirements and other information from the SATS HVO example, RTCA Document DO-236 [9], and from the goal-programming model will be used.

The information components required by the informational infrastructure are timeliness (a function of both initial acquisition and alert time), overall integrity (a function of availability and navigational integrity), and navigational accuracy (a function of position and velocity). Required navigation performance (RNP) constraints [9] have been placed on the airspace as described in the SATS CONOPS.

4.1.2 EPU as a Measure of Uncertainty

RNP is a measure of the navigational performance accuracy required of the population of aircraft operating within a defined airspace. It is comprised of navigational error, computational error, display error, course error and flight technical error. RNP types are established according to navigational performance accuracies in the horizontal plane and are expressed in nautical miles [10]. In order to reduce the complexity in this example, only horizontal navigational errors will be used to provide measures on aircraft separation. These errors will be characterized by the estimate of position uncertainty (EPU), the estimate of velocity uncertainty (EVU) and the containment radius (R_c).

These values will be used to provide bounds on aircraft separation and assurance.

Position estimation error is the difference between the *true position* and the *estimated position* of each aircraft [9]. It is bounded by the EPU. EPU can be described as the radius of a circle centered on an estimated position such that the probability that the actual position lies in the circle is 0.95. A similar description can be made for EVU. Additional positioning assurance is provided by the containment radius (R_c). R_c can be described as the radius of a circle centered on an estimated position such that the probability that the actual position lies in the circle is 0.999.

In the four aircraft approach scenario, position (and velocity) deviations can be viewed as measures of uncertainty (see figure 5 under self separation). The largest of these deviations measured in RNP nautical miles provides insight to establish bounds on the maximum position (and velocity) errors. For this reason, EPU (and EVU) will be used to provide bounds on aircraft separation and assurance.

4.1.3 A Bayesian Network Transition Approach

A Bayesian network probabilistic approach was selected as a tool to transition information from the Level 0 matrix and goal-programming model to the information components required by the informational infrastructure in Level 1. For brief background purposes, a Bayesian network is defined by a set of variables $X = \{X_1, \dots, X_p\}$ and a directed acyclic graph defining a model M of conditional dependencies among the elements of X . A conditional dependency links a *child* variable X_i to a set of *parent* variables Π_i and is defined by the conditional distributions of X_i given the configurations of the parent variables [11]. The primary use of Bayesian networks is in situations that require statistical inference. In a typical inference application, a user has some observed evidence and wishes to infer the probabilities of other events, which have not as yet been observed. Using Bayes' theorem, it is then possible to update the values of all the other probabilities in the network. The major benefit of Bayesian inference over classical statistical inference is that it explicitly describes the fact that observation alone cannot predict the probability of unobserved events,

without some pre-existing information about the latter.

The Bayesian network used to transition from Level 0 to Level 1 for the four aircraft approach example is shown in Figure 6. This model corresponds to a single causal representation of the example. Other causal representations are possible. All of the variables used in the model are discrete where each variable contains a finite number of possible outcomes.

Explanation of the model involves defining the purpose of the model, describing the explanatory input variables, and defining the causal relationships between the variables. The purpose of the causal network model in figure 6 is to provide quantified values for the information components required by the informational infrastructure. The information components are timeliness (a function of both initial acquisition and alert time), overall integrity (a function of availability and navigational integrity), and navigational accuracy (a function of position and velocity). These information components are depicted as gray nodes in Figure 6 and represent the desired outputs of the network.

The input variables are extracted from the Level 0 matrix for the four aircraft approach example (Figure 5) where aircraft #x represents a particular aircraft, aircraft #y represents any other aircraft besides aircraft #x, time window symbolizes the temporal constraint placed on each aircraft to perform its maneuvers, flight leg represents the flight segment, and velocity constraints correspond to the minimum and maximum velocities possible for each aircraft. Other explanatory variables are acquired from the goal programming model such as position deviation (measured in nautical miles) and velocity deviations (measured in meters/second).

The causal relationships between the explanatory and output variables are more easily described by tracing the relationships for each output. An explanation of accuracy is as follows. For each aircraft #x, position and velocity deviations are obtained from the goal programming model per flight leg per time window. The probabilistic representation of EPU can then be computed from the position deviations. An empirical distribution that describes the relationship

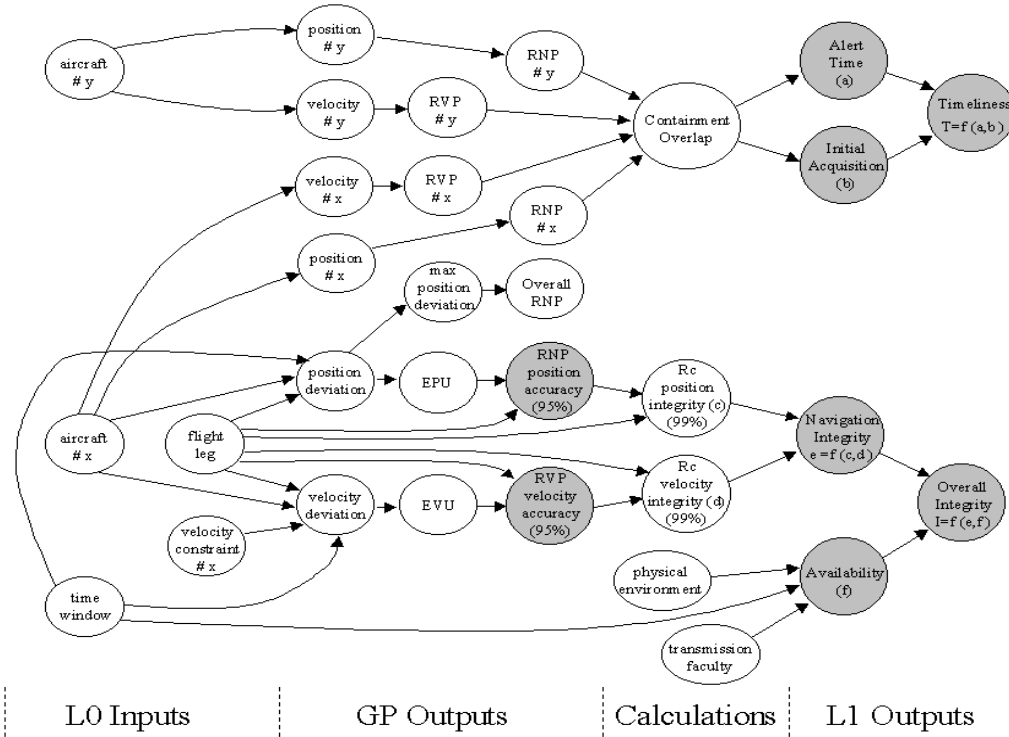


Figure 6. Bayesian Network Level 0 to Level 1 Transition Approach

between position deviations and EPU can be acquired by running a Monte Carlo simulation multiple times with random flight legs and time windows. Using this process, EPU can be used to map position deviations to RNP position accuracies. RNP position accuracy, in this sense, is a measure of the worst-case uncertainty for all aircraft in the local airspace. Similarly, velocity deviations can be mapped to estimated velocity uncertainties to required velocity performances (RVP).

Navigation Integrity is defined as a function of both position integrity and velocity integrity where position integrity is a measure of the containment region required to provide 99.9% position assurance for RNP airspace. R_c , for the example, represents 2 x RNP. Availability is the percentage of time that the services of the system are within required performance limits. It is a function of physical characteristics of the environment, the technical capabilities of the transmitter facilities, and the time window. Probabilistic values for these variables were derived assuming optimal environmental conditions and transmission rates that meet the Level 0 performance requirements. Overall Integrity is a function of navigation integrity and availability.

The causal representation of timeliness stems from the interaction of two aircraft (#x and #y). The RNP and RVP values for each aircraft are computed from the EPU as previously described. The containment overlap variable represents varying degrees of overlap between the containment regions of each aircraft. If we assume a Gaussian position error distribution, containment overlap will represent the percentage of overlap between both aircraft. In like manner, the containment overlap will influence both the amount of time required to alert each aircraft (alert time) and the distance required to acquire information. Figure 7 shows the quantified results for timeliness, integrity and accuracy. Integrity is shown relative to the assurance levels defined by RNP airspace whereas timeliness and accuracy are shown as actual values. The Level 1 matrix of Figure 7 also contains an interpretation of the message content required to support the HVO operation scenario. The interpretation includes three message types and an estimate of the information elements (blocks) and number of symbols per element needed to transfer the required information.

Data Link Service Capability Requirements - Level 1						
Information Requirement	Required Data Link Capability					
	Aid to Visual Aids	Text	Approach	Leg 2	Leg 1	Transition to Terminal Area
Timeliness • Initial Acquisition • Alert Time	10 sec	5 sec	10 sec	30 sec	40 sec	60 sec
Integrity • Availability • Non-Integrity	99%	99.9%	99.9%	99.9%	99%	99%
Accuracy • RNP Pos. (nm) • RNP Neg. (nm)	100 m	OPS w/ SA, 0.6	OPS w/ SA, 0.6	4 m	No Containment Overlap	No Containment Overlap
Information Elements (Msg's) • Current State • Intended State • Capability	728	728	728	728	728	728

Figure 7. Level 1 Matrix

Data Link Application Performance Requirements - Level 2									
Information Element	System Performance Requirements - A2 Equipment								
	Aid to Visual Aids	Approach Surface	Arrival Approach	Control Assistance	Separation Assurance & Sequencing	Flight Path Deviation Planning			
Table Values	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous
Accuracy (1-sigma)	200 m	15 m	20 m	20 m	20 m	20 m	20 m	20 m	20 m
Update Rate	30-50	15 s	15 s	15 s	15 s	15 s	15 s	15 s	15 s
Acquisition Range	10 km	5 km	10 km	10 km	10 km	10 km	10 km	10 km	10 km
# Symbols	54	54	54	54	54	54	54	54	54
Mode Status	Update Rate	Update Rate	Update Rate	Update Rate	Update Rate	Update Rate	Update Rate	Update Rate	Update Rate
Acquisition Range	10 km	5 km	10 km	10 km	10 km	10 km	10 km	10 km	10 km
# Symbols	47	47	47	47	47	47	47	47	47
Update Rate	n/a	n/a	5 s	7 s	12 s	12 s	12 s	12 s	12 s
Acquisition Range	n/a	n/a	n/a	20 km	40 km	40 km	40 km	40 km	40 km
# Symbols	n/a	n/a	n/a	10	10	10	10	10	10
Update Rate	n/a	n/a	n/a	12 s	12 s	n/a	n/a	n/a	n/a
Acquisition Range	n/a	n/a	n/a	20 km	40 km	40 km	40 km	40 km	40 km
# Symbols	n/a	n/a	n/a	10	10	10	10	10	10

Figure 8. Level 2 Matrix

4.2 Transitioning Between Level 1 and Level 2

The Level 1 matrix provides the information requirement basis for selection of a data link service that adequately supports the desired operations. The Level 2 Matrix (Figure 8) defines the specific performance requirements of the information elements that provide the selected data link service's timeliness, accuracy, and integrity. The performance value of each information element that is required to enable each capability is available in the MASPS [12] for the selected data link service. For this example, the transition to Level 2 was accomplished by a manual search of RTCA Minimum Aviation System Performance Standards (MASPS) documents for data link services, which yielded the Level 2 matrix in Figure 8. For the HVO scenario, one data link service that provides sufficient information performance capability is Automatic Dependent Surveillance Broadcast (ADS-B) [15]. An automated search process would be preferable to a manual search process for the transition to Level 2. The process would require the electronic availability of data link MASPS documents to a widely distributed information infrastructure, and an appropriate search engine. Wide area information network capabilities are proposed [3] that enable such an automated search process.

4.3 Transitioning Between Level 2 and Level 3

The transition to Level 3 specifies the performance of the underlying technology in terms of the bottom three layers of the Open System Interconnect (OSI) protocol. Layer 3, the Network

Layer, establishes the protocol by which data packets are exchanged across the network. Layer 2, the Data Link Layer, provides access to the physical communication channel and performs error detection. Layer 1, the Physical Layer, provides the physical signal-in-space channel by which messages are transmitted and received.

4.3.1 Purpose of This Transition

Level 3 provides the minimum technology performance required to enable the data link service. It derives design parameter values from the data link application performance requirements, which establish the communication system designer's trade space. The following discussion addresses the Physical Layer only. An excellent discussion of the application of new advances in Petri Net theory to media access control design in the Data Link Layer is found in reference [13].

4.3.2 A Model-Based Transition Approach

The Level 3 approach uses Shannon's Information Capacity Theorem [14] and the Level 2 Matrix (Figure 8) to derive values for the critical parameters that bound the design space. The primary parameters of interest are the signal energy-per-bit to noise spectral density ratio (E_b/N_0), the bandwidth efficiency (R_b/B), the modulation method and number of discrete levels M each symbol can assume, and the average probability of symbol error (P_e). The parameter values are computed using equations (6) and (7), and update rate, availability requirement, and message content information from the Level 1 and 2 Matrices. Phase Shift Keying (PSK) M-ary

modulation is assumed [14, 15]. In equation (7), erfc is the complementary error function [14].

$$R_b = .5B \log_2 \left(1 + \frac{E_b}{N_o} \frac{R_b}{B} \right) \quad (6)$$

$$P_e = \text{erfc} \left(\sqrt{\frac{E_b}{N_o}} \sin \frac{\pi}{M} \right) \quad (7)$$

The inputs to the computation are $P_e = 10^{-3}$ (1 – availability), total number of symbols per transmission $K = 203$ (# aircraft), minimum transmit interval = 1.5 seconds, and number of transmitting aircraft = 4. By varying M , the trade space between E_b/N_o and R_b/B can be investigated.

5 Conclusions

The future National Airspace System can be viewed as composed of highly coupled dissimilar functions with dependent yet conflicting objectives. The information network that enables efficient, effective, reliable, and safe execution of these functions will exhibit similar appearance and behavior. Selectors and designers of data link architectures that implement the networks will be required to make optimal decisions in this complex environment. The purpose of the data link decision framework is to authorize a methodology that manages the interdependencies and the resulting complexity of the decision in a way that allows for intelligent and meaningful analysis in a systems-oriented fashion. The data link decision framework is a decision-analytic process that simplifies data link complexity by partitioning the analysis among four different levels (Levels 0-3). Subsequently, each of the four levels partitions the multi-objective analysis from high-level constituents (mostly qualitative decision variables) to low-level constituents (quantitative decision variables). Quantitative techniques are developed to perform the transition between levels. The methodology is demonstrated with an example.

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